Comparison of Laser Produced Plasma and Discharge Produced Plasma as a Source for Soft X-Ray Microscopy

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Abstract

We compare two table top sources of extreme ultraviolet (XUV) radiation - laser produced plasma (LPP) and discharge produced plasma (DPP), with regard to cell imaging in the soft x-ray regime. Nitrogen plasma is ideal for monochromatic radiation with wavelength λ = 2.88 nm, which corresponds to the quantum transition $1s^2$-1s2p of helium like nitrogen ion. This wavelength is located in the water-window region, thus it provides the natural contrast between water and carbon-based substances, e.g. proteins.

LPP source was developed in Laser-Laboratorium Göttingen e.V., Germany, plasma induced by Q-switched Nd:YAG laser (λ = 1064 nm, 600 mJ, 7 ns pulse) focused into nitrogen gas-puff target. The typical photons flux was 1.5×10^{12} photons/(sr x line x pulse) for input nitrogen pressure p = 13 bar. The size of the plasma spot was 0.2 x 0.4 mm.

DPP source was built in-house, plasma was generated by a current discharge through a 10 cm long, 3.2 mm inner diameter ceramic capillary filled with nitrogen gas. The charging voltage was 90 kV and the maximum current was 27.5 kA. Average photons flux was 5×10^{13} photons/(sr x line x pulse) and plasma spot had FWHM 0.3 mm.

Experimental details

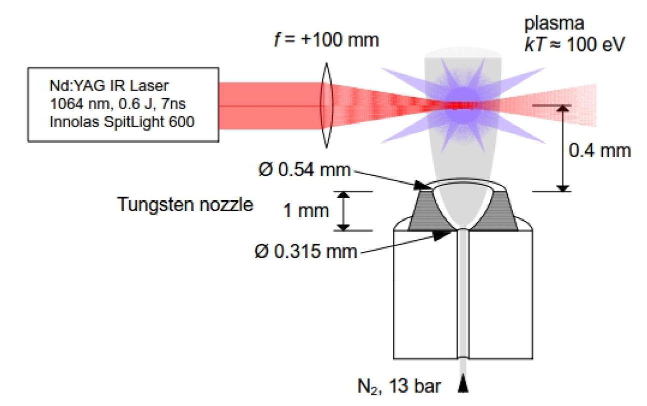

Fig. 1: The schematic of laser produced plasma soft X-ray source

LPP

The plasma was formed by Inverse Bremsstrahlung absorption of a pulsed IR laser radiation in the nitrogen gas-puff target of density 3.7×10^{-4} g/cm^3. The gas-puff target was produced by pulsed injection of pressurized (13 bar) gaseous nitrogen by a high-pressure piezoelectrically actuated valve through a conical tungsten nozzle into the focus of the IR laser beam. The Nd:YAG laser is operating at 1064 nm wavelength with repetition rate of 3 Hz. The beam is focused onto a 60 µm diameter spot using a 100 mm focal length lens.

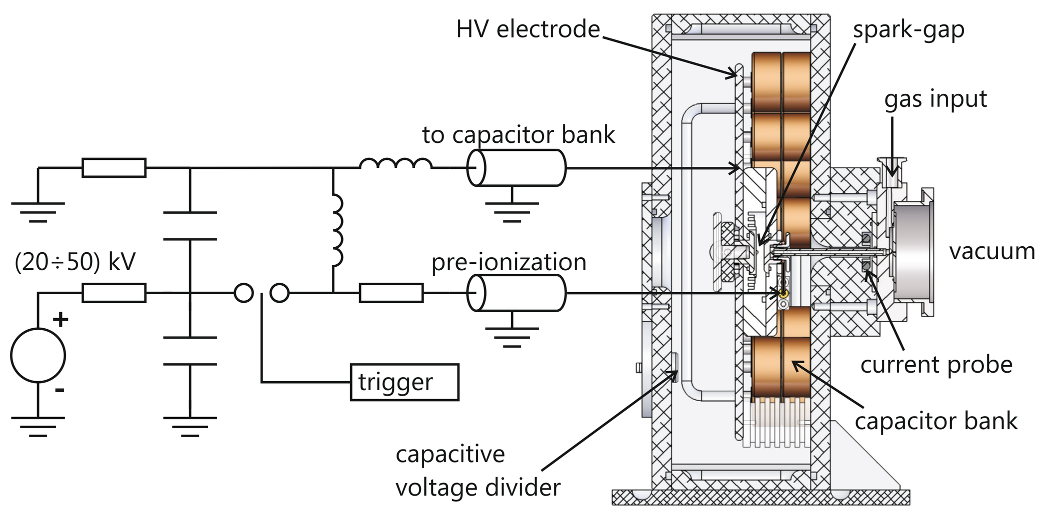

Fig. 2: Capillary plasma driver and charging circuit

DPP

The ceramic capacitor bank with a maximum capacity of 21 nF was pulsed charged by March-Fitch generator to 90 kV, and switched by self-breakdown spark-gap. Before the main discharge a 20 - 35 A, 3 µs long current pulse pre-ionized nitrogen in the capillary and prepared a uniform conducting channel. The alumina (Al_2O_3) capillary was filled with nitrogen through a hollow in the electrode on its ground side. Radiation was also emitted through this hole.The system was enclosed in duralumin housing in order to reduce electromagnetic noise.

Results

The radiation emitted from the nitrogen plasma was measured by high speed AXUV PIN diode for both sources, the titanium filter with thickness of 500 nm was used to separete the spectral line 2.88 nm. The measurement setup is shown in fig. 3 and fig. 5. Capillary current was measured by Rogowski coil. XUV energy was determined by numerical integration. Measurement of nitrogen-based source photon flux is carried out in fig. 7. The maximal value of photons per sr per pulse for LPP is 1.8×10^{12}, which corresponds to energy 0.12 mJ per pulse for input energy 640 mJ. The maximal value of photons per sr per pulse for DPP is 5.5×10^{13}, which corresponds to energy 3.8 mJ per pulse for nitrogen pressure 50 Pa and input energy 85 J. Thus, DPP has more than 30 times higher photon flux than LPP, with appreciably longer duration of pulse (fig. 8). Also a spatial distribution of nitrogen plasma was obtained using a pinhole camera with 30 µm diameter pinhole. LPP had an elongated shape with dimensions 0.2 x 0.4 mm (fig. 4). The plasma spot of DPP had a circular shape with diameter 0.3 mm (fig.6).

LPP

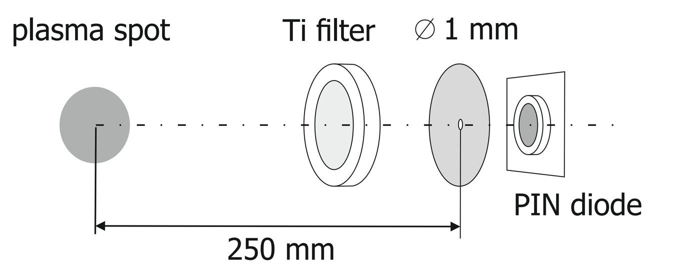

Fig. 3: XUV Power measurement setup - LPP

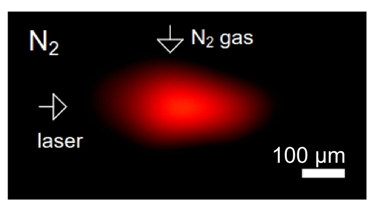

Fig. 4: Spatial distribution of the soft X-ray emission from laser-produced plasma in N_2 gas puff target

DPP

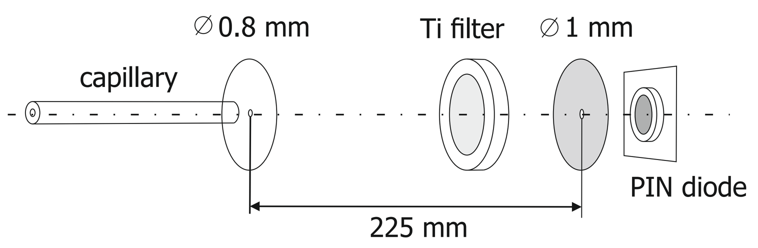

Fig. 5: XUV Power measurement setup - DPP

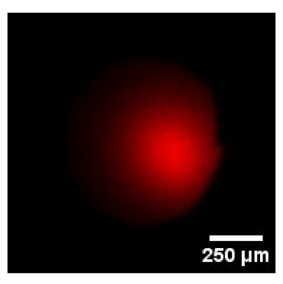

Fig. 6: Spatial distribution of the soft X-ray emission from discharge produced plasma in N_2

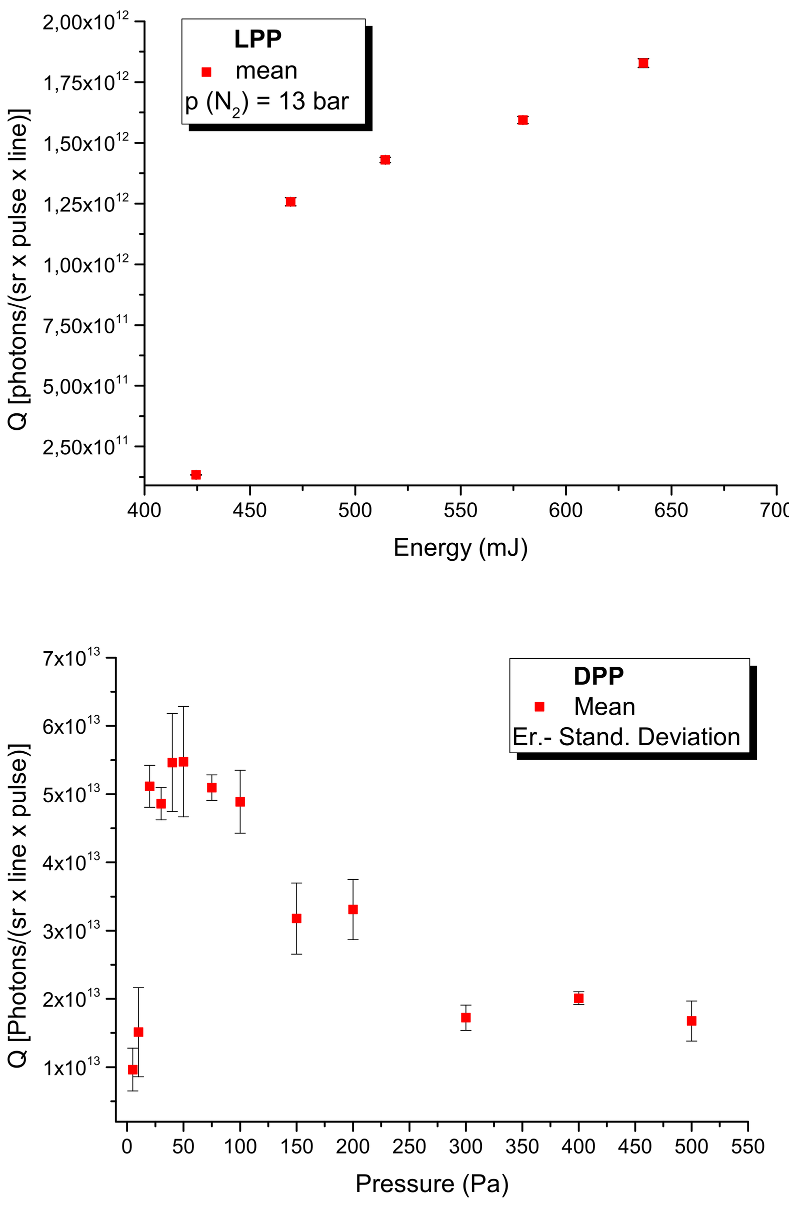

Fig. 7: Photon flux vs. laser input energy - LPP (top), photon flux vs. nitrogen pressure - DPP (bottom)

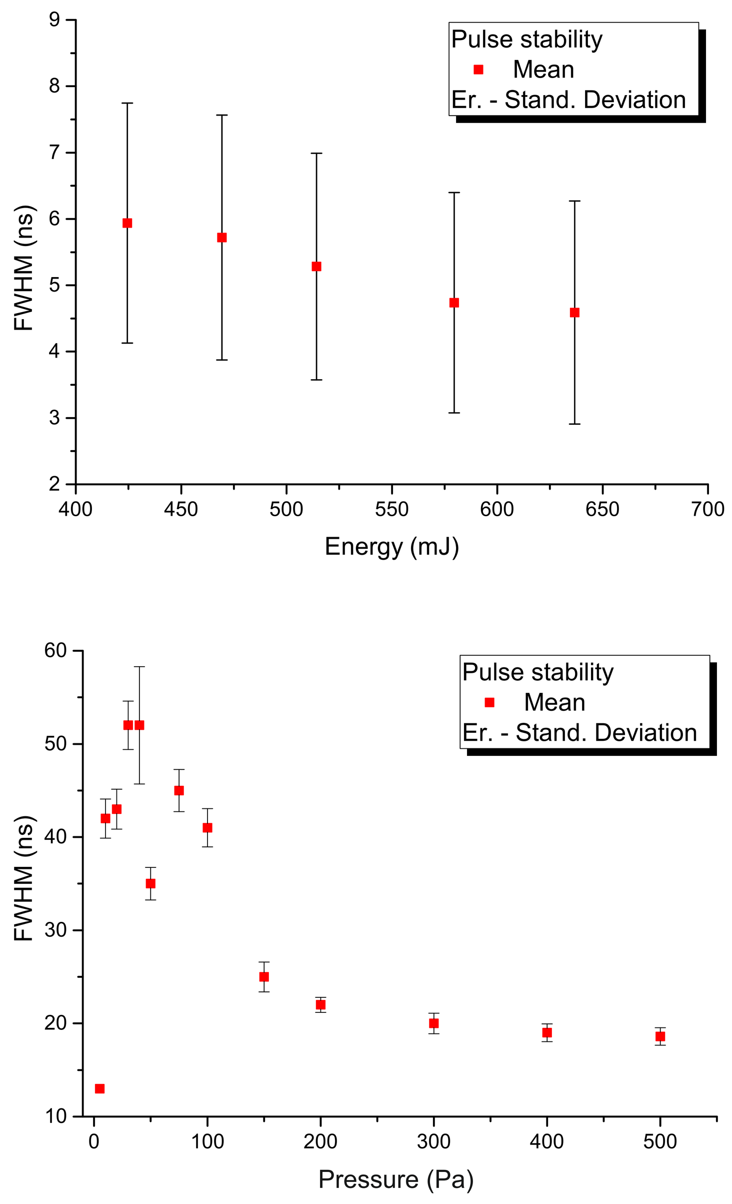

Fig. 8: Length of pulses (FWHM) vs. laser input energy - LPP (top), length of pulses (FWHM) vs. nitrogen pressure - DPP (bottom)

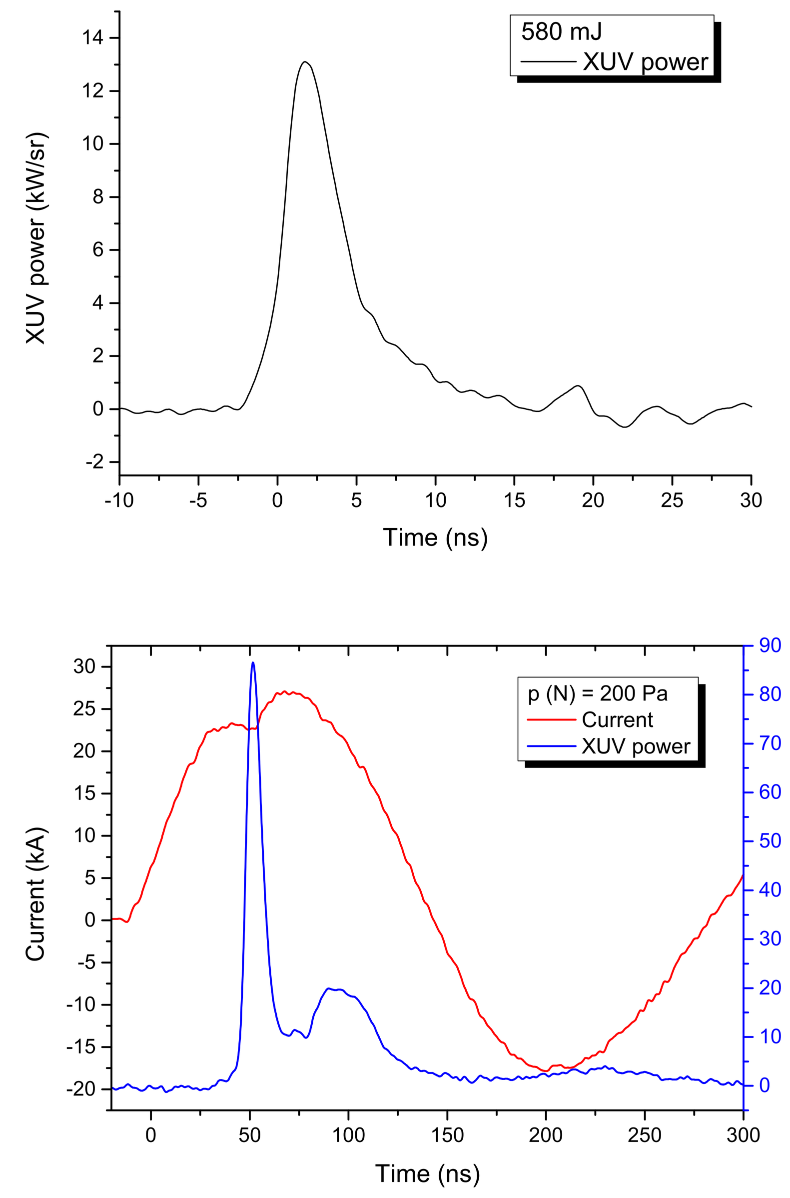

Fig. 9: Typical pulse of LPP (top), DPP (bottom)

Conclusion

The laser produced plasma and the discharge produced plasma in nitrogen have been proved as the efficient water window radiation table-top sources suitable for soft X-ray microscopy. The disadvantage is a low repetition rate 2 Hz for DPP and 3 Hz for LPP. The discharge produced plasma in nitrogen has 30 times higher photon flux than the laser produced plasma in nitrogen. The presented sources are comparable with ([3], 4×10^9 photons per pulse, [4], 10^{12}photons/(sr x pulse)) table-top soft X-ray sources using as a basis for soft X-ray microscope.

LPP

Photon flux per sr per pulse:	1.8×10^{12} photons
Energy/(pulse per sr):	0.12 mJ
Source efficiency:	1.875×10^{-4}
Peak power per sr:	17.6 kW

*for input energy 640 mJ and nitrogen pressure 13 bar

DPP

Photon flux per sr per pulse*:	5.5×10^{13} photons
Energy/(pulse per sr)*:	3.8 mJ
Source efficiency*:	4.47×10^{-5}
Peak power per sr':	87 kW

*nitrogen pressure 50 Pa, 'nitrogen pressure 200 Pa

Future work

The photon flux of LPP can be improved by e.g. increasing the density of the target or by using a picosecond laser. Soft X-ray emission of the DPP source can be increased by optimizing the capillary dimensions and increasing the input voltage. According to the computer simulation the maximal current can reach 33 kA [1].
For Soft X-ray imaging and spectroscopy applications we foresee to implement a condenser and a Fresnel zone plate with outer zone width of less than 100 nm.

Acknowledgement

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References

[1] M. Nevrkla, J. Novak, A. Jancarek, P. Vrba, M. Vrbova: Characterization of Capillary Discharge Water-Window Radiation Source. 2012 International Workshop on EUV and Soft X-Ray Sources. Dublin, Ireland.
[2] P. Bruza: Pulsed Plasma Soft X-Ray Source in Biomedical Research. PhD Thesis. Czech Technical University in Prague, 2014.
[3] P. W. Wachulak et al.: Sub 1µm resolution „water-window" microscopy using a compact, laser-plasma SXR source based on a double stream gas-puff target. Nuclear Instrument and Methods in Physics Research B 311 (2013) 42-46.
[4] H. M. Hertz et al.: Laboratory cryo soft X-ray microscopy. Journal of Structural Biology 177 (2012) 267–272.